TOWARDS DEMONSTRATION OF A MOT-BASED CONTINUOUS COLD CS-BEAM ATOMIC CLOCK

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Abstract

Laser-cooled low-velocity (v < 10 m/s) atomic beams have been considered to be feasible cold atom sources in developing compact and highly stable atomic clocks for satellite applications. A cold atomic beam can be realized by laser-accelerating an ensemble of ultra-cold (T < 1 mK) atoms from a laser-cooled magneto-optical trap (MOT). This technique has the unique advantage of generating a useful cold atomic beam just outside the volume of a MOT and, hence, can greatly reduce the size of the atomic clock physics package. In this paper, we present our design and experimental results towards demonstration of a MOT-based cold Cs-beam atomic clock. We have generated a continuous cold Cs beam from a Cs MOT and have determined the typical longitudinal velocity of the Cs beam by Time of Flight (TOF) method to be 7 m/s with a velocity spread of 1 m/s. By adjusting the MOT parameters, the atomic beam velocity can be tuned continuously, with the velocity spread remaining to be 1 m/s. In order to separate the atomic beam from the MOT laser beam, we have used a one-dimensional optical molasses to efficiently deflect the cold Cs beam through an angle of 30 degrees. The 1-D optical molasses is set up in such a way that the molasses laser beams are perpendicular to the final atomic beam propagation path. Thus, the Cs-beam velocity components along the molasses axis are efficiently damped to nearly zero, while the Cs velocity component along the final atomic beam propagation path is unaffected. Our simulation indicates that a deflection efficiency of 100% is achievable for MOT-based cold atomic beams. Our cold Cs beam has an instantaneous atomic flux of 3.6×10^{10} atoms/s when operated in pulsed mode and an estimated continuous beam flux of 2×10^{8} atoms/s. With a compact Ramsey cavity of 13 cm in length, we have estimated a short-term, shot-noise limited Allan standard deviation of $2.7 \times 10^{-13}\ \tau^{-1/2}$ (τ is the averaging time) for the atomic clock in this work. Experiments of generating Ramsey interference fringes using the deflected, "dark" cold Cs atomic beam are in progress.

INTRODUCTION

The global navigation and communication satellite programs have continuing needs for better atomic frequency / time references. Laser-cooled low-velocity (v < 10 m/s) atomic beams are practical cold atom sources for compact and highly stable atomic master oscillators in space applications **[1-5]**. Using laser cooling and trapping technology, there are two demonstrated techniques to produce cold atomic beams. The first is to use a Zeeman slower to directly laser-decelerate a thermal atomic beam to near zero velocity through a distance of about 1 meter **[6-8]**. The second, on the contrary, is to laser-accelerate an ensemble

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of ultra-cold (T < 1mK) atoms from a laser-cooled magneto-optical trap or MOT. The unique advantage of this technique is that a useful low-velocity atomic beam is generated right out of the volume of the MOT. The basic idea is to introduce a controlled leak to a magneto-optical trap (MOT) by modifying the trapping potential in such a way that the MOT functions like a cold atom funnel, with which thermal atoms are captured, cooled, and then pushed out to form an atomic beam **[9-14]**. Since the atomic beam thus formed originates from an ensemble of cold atoms at ~ 100 μK, very low beam velocities can be obtained within a short distance through a controlled laser acceleration process, hence making it possible to significantly reduce the size of a cold-atom atomic clock system.

In this paper, we first discuss our physics package design of a MOT-based cold continuous Cs-beam atomic clock using a short Ramsey cavity. Then we report our progress in the experiments towards demonstration of such a cold-atom clock. The progress includes observation and investigation of a low-velocity Cs atomic beam generated from a vapor-cell Cs magneto-optical trap and the optical deflection of the Cs beam using a 1-D optical molasses. In our system, no specially fabricated optics are used inside the vacuum chamber. Our simulation indicates that a MOT-based cold atomic beam can be effectively deflected through a large angle with 100% efficiency. Finally, we will discuss the performance prospects of the cold continuous Cs-beam atomic oscillator in this work.

PHYSICS PACKAGE AND EXPERIMENTS

PHYSICS PACKAGE

The physics package design, as shown schematically in Figure 1, has been discussed in a previous paper **[5]**. Briefly, the slow-velocity Cs atomic beam is generated from a Cs magneto-optical trap (MOT) and deflected by an angle of 30 degrees using a 1-D optical molasses. The atomic beam needs to be deflected, because when it leaves the MOT where Cs atoms are cooled to sub-milliKelvin temperatures, it co-propagates with one of the MOT laser beams. This laser light would cause errors in an atomic frequency standard based on the cold atomic beam due to the light-shift effect. In order to avoid laser-atom interactions during the actual generation of atomic clock signals, the cold Cs atomic beam has to be spatially separated from the laser beam and maintained in the "dark." The retro-reflected laser beams form the 1-D optical molasses, which damps the velocity component perpendicular to the Cs-beam final propagation direction while leaving the velocity component along the final propagation path unaffected. Upon deflection of the Cs beam, optical pumping prepares Cs atoms into the magnetic-insensitive $F=4$, $m_F=0$ (or $F=3$, $m_F=0$) clock level before they enter a short Ramsey microwave cavity of 13 cm in length. Ramsey interference fringes and atomic clock signals will be generated via laser-induced fluorescence near the output of the microwave cavity. The 9.2 GHz microwave frequency from a tunable OCXO-based synthesizer will eventually be locked to the Cs atomic hyperfine transition to provide long-term frequency stability for the clock. Unlike other cold-atom atomic clock designs **[1-3,15]**, our physics package design allows the cold Cs beam atomic clock to operate in a continuous mode for better clock stability.

MOT-BASED COLD CS BEAM

We generated the low-velocity Cs atomic beam from a vapor-cell MOT of Cs atoms **[13]**. The MOT cools 8×10^7 Cs atoms to ~ 300 μK. The Cs trap has a loading time constant of 0.4 s and is accommodated in an ultrahigh vacuum chamber with a background pressure of 6×10^{-10} torr. A 150 mW Distributed-Bragg-Reflection (DBR) diode laser at 852 nm is used for cooling and trapping. The MOT laser is red-detuned by 20 MHz (~ $4\delta_0/\gamma$) from the $6^2P_{3/2}$ $F'= 5$ hyperfine level. To form a Cs atomic beam, Cs atoms are exported from the Cs MOT by making one of the six trapping laser beams into a hollowed laser beam. This configuration generates a controlled leak tunnel of the atomic trap while the MOT still captures and cools Cs atoms from the surrounding Cs vapor. When the leak tunnel is established, the trapped Cs atoms feel a net spontaneous force from the acceleration laser beam, that is, the trapping laser beam propagating

in the opposite direction of the hollowed trapping beam. Figure 2 shows the image of the laser-induced fluorescence of the MOT and the Cs atomic beam in the vicinity of the trap volume. The bright spot is the Cs MOT cloud and the Cs beam is seen to the right of the trap. Note that Figure 2 is a snapshot of continuous operation of the MOT-based cold Cs atomic beam system.

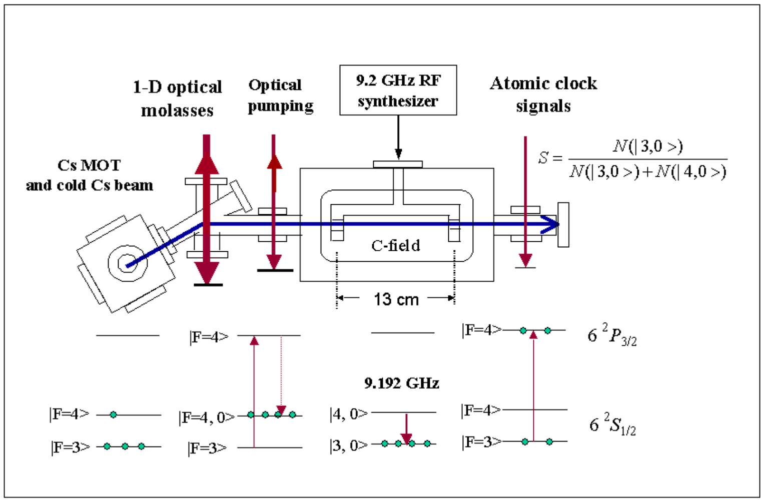


Figure 1. Schematic diagram of the clock physics package. The MOT laser beams are not shown here. The Cs atomic beam is deflected by 30 degrees using a 1-D optical molasses. Also plotted is the relevant Cs atomic energy levels as well as the optical pumping, clock interrogation, and clock signal generation processes. The dimensions of components are not in scale.

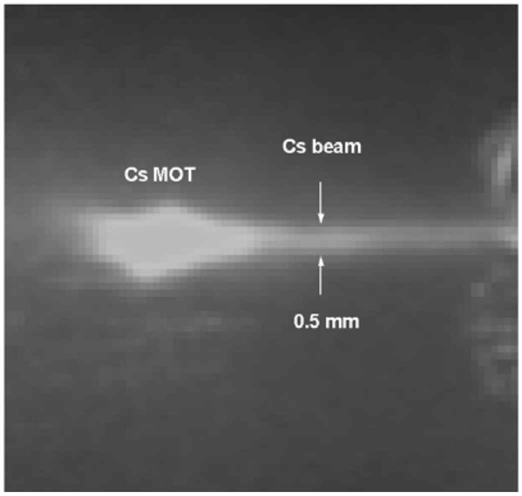


Figure 2. Laser-induced fluorescence image of the MOT-based continuous Cs atomic beam. The bright spot is the trapped cold Cs atom cloud and the relatively weaker narrow line is the Cs atomic beam traveling to the right.

The mean velocity of the MOT-based Cs beam was measured by the Time of Flight (TOF) method when the MOT-beam system was operated in a semi-continuous mode. Figure 3 shows a typical time of flight signal of the cold Cs beam, giving an averaged beam mean velocity of 7.3 m/s under typical experimental conditions. The line width (FWHM) of the TOF signal in Figure 3 corresponds to an atomic beam velocity spread of 1 m/s. This velocity spread is mainly due to the initial spatial and momentum distribution of the Cs atoms in the MOT volume (V ~ 1 mm^3 and T ~ 300 μK). Assuming all the 8×10^7 trapped Cs atoms pass through the probe laser beam in 2.2 ms, we have an instantaneous beam flux of 3.6×10^{10} atoms/s. If the cold Cs beam is operated in a continuous mode and the Cs beam is the predominant trap loss, the continuous beam flux is approximately equal to the Cs MOT loading rate, which is measured as 2×10^8 atoms/s.

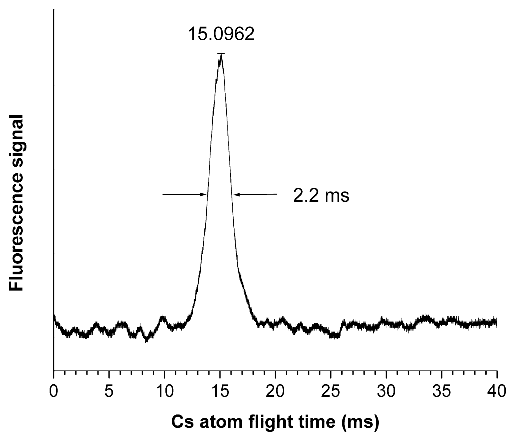


Figure 3. Time of flight measurement of Cs atomic beam velocity. The peak flight time gives a mean beam velocity of 7.3 m/s and the width (FWHM) of the signal indicates a velocity spread of 1 m/s.

Our experiments also demonstrated that the Cs-beam velocity is tunable by adjusting the MOT parameters. Using the time of flight technique, we have been able to measure the velocity dependence on the acceleration laser frequency, the MOT magnetic field gradients, and the acceleration laser intensity. The results have been reported in detail in Reference **[13]**. Briefly, the Cs atoms are accelerated by one of the trapping laser beams, whose frequency is red-detuned by a few times of the natural line width γ(5.18 MHz). A larger red detuning, δ_0/γ, reduces the velocity of the Cs beam. Here, $\delta_0 = \nu_L - \nu_0$ is the red detuning of the acceleration laser and ν_L and ν_0 the laser frequency and the atomic resonance frequency, respectively. The Cs-beam velocity decreases as the magnetic field gradient increases. This is because the Zeeman effects from the inhomogeneous magnetic field increase the total off-resonance detuning of the acceleration laser, resulting in a reduced spontaneous force as indicated. The ability to control the atomic beam velocity is useful in implementing a highly stable atomic beam by actively stabilizing the beam velocity.

OPTICAL DEFLECTION OF COLD CS BEAM

Next, we constructed a one-dimensional optical molasses using a pair of frequency-stabilized, retro-reflected laser beams from an external cavity diode laser (Toptica Photonics DL-100). The diode laser was locked to the same Cs hyperfine transition as the MOT laser and was red-detuned by 10 MHz (~$2\delta_0/\gamma$) from the $6^2p_{3/2}$ $F = 5$ level. The 1-D molasses laser beams produce Doppler cooling effects along the axis of the molasses through the radiation force. As shown in Figure 4, the axis of the 1-D optical molasses is

perpendicular to the final atomic beam propagation direction (a 30-degree bend from the original direction of the Cs beam). Thus, when the cold Cs atomic beam interacts with the 1-D optical molasses, atomic velocity components along the molasses axis are effectively damped to near zero, while the Cs beam velocity component along the final atomic beam propagation path is unaffected. Consequently, the cold Cs beam is bent by the optical molasses through an angle of 30 degrees. Using the laser-induced radiation force model **[16-17]** written in Equations (1) and (2) below:

$$m\frac{d^2x}{dt^2} = -\beta\frac{dx}{dt} \qquad (1)$$

$$\beta = 4\hbar k^2 \frac{S_0(\frac{2\delta}{\gamma})}{[1+2S_0+(\frac{2\delta}{\gamma})^2]^2} \qquad (2)$$

we calculated the atomic beam trajectory when the Cs atoms interact with the 1-D optical molasses, as illustrated in Figure 4. Here in Equations (1) and (2), m is the mass of Cs atoms and $\delta = \nu_L - \nu_0$ the red detuning of the molasses laser. $S_0 = I / I_s$ is the intensity saturation factor and k the wave vector of the molasses laser. Our trajectory simulation indicates that the MOT-based cold Cs beam can be deflected with 100% efficiency under the experimental conditions. This is because the MOT-generated cold Cs beam has a very narrow velocity spread (Δv ~ 1 m/s), while the 1-D optical molasses can capture and deflect atoms with velocities up to ~ 20 m/s. Consequently, all Cs atoms in the cold atomic beam at a nominal speed of ~10 m/s can be captured by the molasses and deflected effectively through a 30° angle.

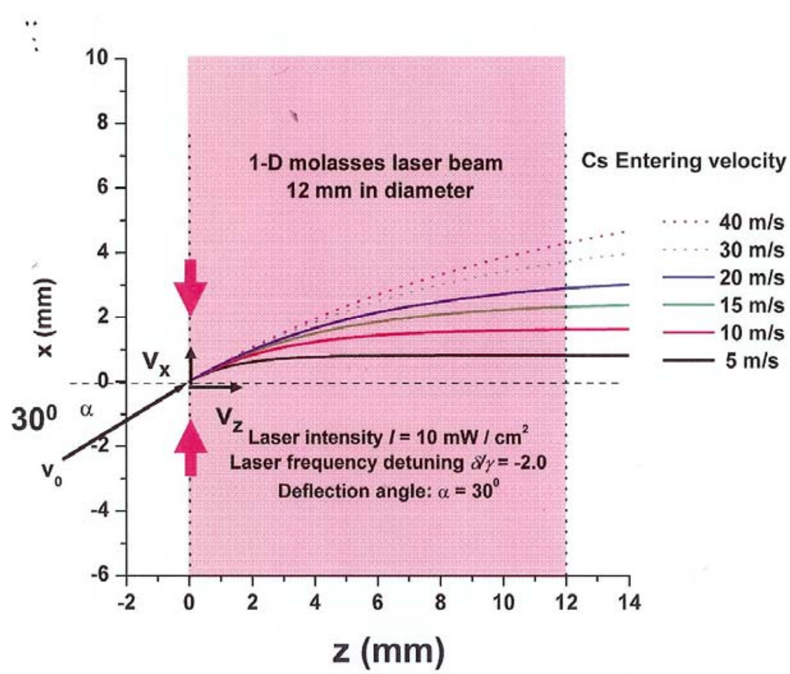
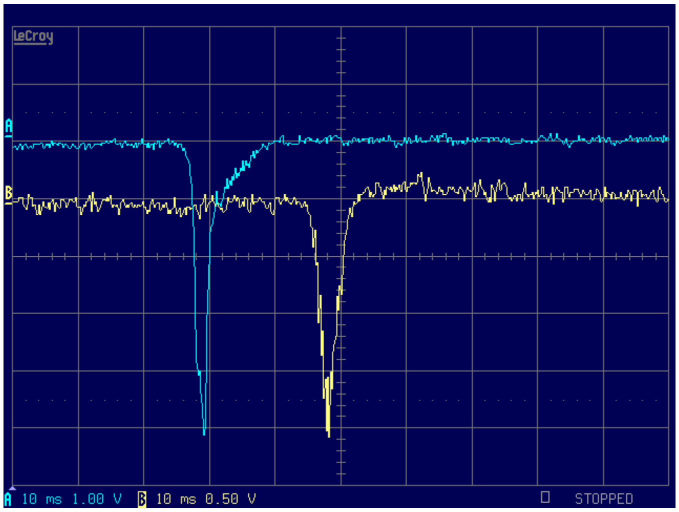


Figure 4. Deflection of Cs atomic beams by 1-D optical molasses and trajectory calculation.

Using this technique, we have experimentally demonstrated that the MOT-based cold Cs-beam was bent through 30° and was detected in the atomic clock signal detection region. Briefly, the deflected Cs atomic beam was observed using laser-induced fluorescence (LIF) in the atomic clock signal detection region, which is about 30 cm downstream from the 1-D optical molasses. Figure 5 shows a typical TOF measurement of LIF signals of the Cs beam when the Cs atoms travel through the optical molasses (the blue curve) and through the atomic clock signal probe point (the yellow curve). The uniform Cs beam velocity can then be accurately measured by the time interval between the two LIF signals in Figure 5. By adjusting the experimental parameters, we obtained slow-moving Cs atomic beams with uniform velocities tunable from 7 m/s to about 20 m/s. During the optimization experiment, we observed that the atomic beam deflection efficiency is very sensitive to the optical molasses laser frequency, while it is less sensitive to the molasses laser intensity. This observation agrees with the results of our trajectory calculation **[18]**. In addition, we also found in the experiment that an optical pumping laser beam was needed in the deflection region for efficient bending of the Cs atomic beam.



Time (10 ms/div)

Figure 5. Time-of flight (TOF) laser-induced fluorescence (LIF) signals of cold Cs atomic beam operated in pulsed mode. The blue curve is signals induced by the 1-D optical molasses in the Cs beam deflection region as shown in Figure 1. The yellow waveform is observed in the atomic clock signal detection region after the cold Cs beam is deflected through an angle of 30 degrees. The time scale is 10 ms/div. The signal intensity is in arbitrary units.

From Figure 5, we also see that the deflected Cs beam appears to have slightly larger velocity spread than that before being deflected. We attributed this to the poor spatial mode of the 1-D optical molasses laser beam. Atoms entering the intense region of the laser beam are deflected more quickly than atoms entering the weak region, causing differences in arrival times of atoms in the detection point. To resolve this problem, we have set up an optical fiber spatial filter for the molasses laser and obtained a perfect TEM_{00} mode laser beam with a 70% coupling efficiency. It is expected that identical velocity spreads before and after the Cs beam is deflected will be observed using the improved molasses laser beam. Finally, it is worth noting that the Cs beam deflection technique used in this work will also be useful for

spatial modulation of neutral atomic beams in atom optics, atom deposition, and atom interferometer applications.

CLOCK PROSPECTS AND CONCLUSIONS

From the cold Cs beam parameters in this work, we have estimated that the MOT-based continuous cold Cs-beam atomic clock has an Allan standard deviation of $\sigma_y(\tau) = 2.7 \times 10^{-13}\ \tau^{-1/2}$ (τ in second) for its short-time frequency stability under the shot-noise approximation **[19-20]**. Table 1 lists the estimated clock parameters. Plotted in Figure 6 is the Allan standard deviation $\sigma_y(\tau)$ as a function of the averaging time, giving a 1-day frequency stability of 9.2×10^{-16}.

In conclusion, we have designed the physics package of a continuous cold Cs-beam atomic clock. In our design, the atomic clock will be able to operate in a continuous mode with a MOT-based, "dark" Cs atomic beam. Our clock design uses optical pumping for clock state preparation and laser-induced fluorescence for clock signal detection. To date, we have experimentally demonstrated a MOT-generated cold Cs atomic beam, which travels at a longitudinal velocity tunable in a range of 7-20 m/s, with a velocity spread of ~1 m/s. In order to avoid light-shift effects in the Cs-beam clock operation, we have separated the MOT-generated Cs beam from the MOT laser beam by deflecting the Cs beam through an angle of 30° using a 1-D optical molasses. Our experiment and trajectory calculation both indicate that 100% deflection efficiency is achievable by this technique for MOT-based cold atomic beams. Experiments of generating Ramsey interference fringes and atomic clock signals using the cold Cs beam reported in this paper are underway in our laboratory.

Table 1. Estimated cold Cs-beam atomic clock parameters in this work.

Beam flux (F)	2×10^8 atoms/s
Beam velocity (v)	7 m/s
S/N ratio (shot-noise limited)	1.4×10^4
Ramsey separated-field cavity length (L)	13 cm
Clock line width ($\Delta\nu$)	35 Hz
Clock frequency (ν_0)	9.192 GHz
Clock short-term stability ($\sigma_y(\tau)$ τ in second)	$2.7 \times 10^{-13}\ \tau^{-1/2}$

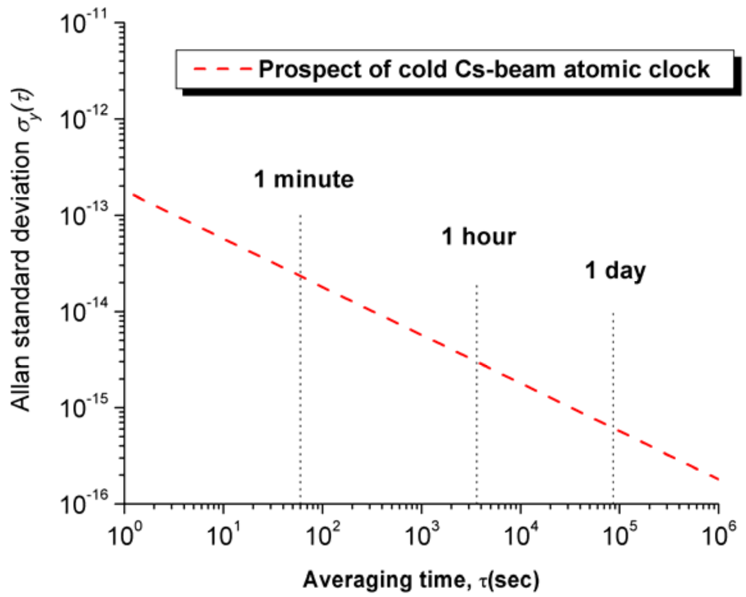


Figure 6. Estimated Allan standard deviation of the cold Cs-beam atomic clock in this work.

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